Vol. 5/4, pp. 219–230

http://www.urbanfischer.de/journals/ppees

Perspectives in Plant Ecology, Evolution and Systematics

Does artificial snow production affect soil and vegetation of ski pistes? A review

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Received: 8 October 2002 · Revised version accepted: 10 January 2003

Abstract

The production of artificial snow and the use of snow additives in ski resorts have increased considerably during the last 20 years. Their ecological consequences are the subject of environmental concerns. This review compiles studies about the ecological implications of ski pistes preparation in general and of artificial snow production. The main direct impacts of ski piste preparation on the vegetation are related to the compaction of the snow cover, namely the induction of soil frost, the formation of ice layers, mechanical damage and a delay in plant development. The vegetation reacts with changes in species composition and a decrease in biodiversity. Artificial snowing modifies some of these impacts: The soil frost is mitigated due to an increased insulation of the snowpack, whereas the formation of ice layers is not considerably changed. The mechanical impacts of snow-grooming vehicles are mitigated due to the deeper snow cover. The delay of the vegetation development is enhanced by a considerably postponed snowmelt. Furthermore, artificial snowing induces new impacts to the alpine environment. Snowing increases the input of water and ions to ski pistes, which can have a fertilising effect and hence change the plant species composition. Increasingly, snow additives, made of potentially phytopathogenic bacteria, are used for snow production. They enhance ice crystal formation due to their ice nucleation activity. Although sterilised, additives affected the growth of some alpine plant species in laboratory experiments. Salts are applied not only but preferably on snowed pistes to improve the snow quality for ski races. The environmental impacts of most salts have not yet been investigated, but a commonly used nitrate salt has intense fertilising properties. Although snowing mitigates some of the negative impacts of ski piste preparation in general, new impacts induced by snowing could be non-beneficial to the vegetation, which, however, has yet to be clarified.

Key words: fertilisation, ice nucleation activity, INA, *Pseudomonas syringae,* snowpack, snow additives

Introduction

Winter tourism has become an important economic sector in the mountain regions of the world (e.g. Abegg et al. 1997; Elsasser & Messerli 2001). Simultaneously, the creation and maintenance of ski pistes has been one of the major environmental concerns in these regions and a subject of numerous studies (e.g. Mosimann 1985; Bayfield 1996; Urbanska 1997; Titus 1999). The direct impacts of ski piste preparation on

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1433-8319/03/5/04-219 $ 15.00/0

the vegetation are primarily caused by the compaction of the snow cover which results in a denser and less deep snow cover with an increased thermal conductivity and decreased gas permeability (Newesely 1997; Rixen 2002). As a consequence, plants can suffer from frost damage, oxygen deficiency, infection by fungi and pathogens, a delay in plant development and mechanical damage to the plant tissue (Cernusca 1989; Newesely 1997; Stoeckli & Rixen 2000). Changes in plant species composition and a decrease in biodiversity are the result (Rixen 2002).

The increased soil frost on ski pistes is caused by increased thermal conductivity of dense snow. March snow on Swiss ski pistes has an average density of approximately 480 kg m^{-3} because of compaction by snow-grooming vehicles while incompact snow has only 350 kg m^{-3} (Rixen 2002). As the thermal conductivity is a logarithmic function of the snow density (Sturm et al. 1997), the heat flux through the compacted snow cover is much higher than through undisturbed snow. The thermal conductivity in compacted natural snow was found to be about two times higher than in incompact natural snow (Geiger 1961; Cernusca et al. 1990). Together with the thermal conductivity of the snow, the air temperature and the snow depth are responsible for the cooling of the soil below (Sturm et al. 1997). Under the compacted dense and thin snow cover of ski pistes, severe and long-lasting soil frost occurs (Newesely 1997; Rixen 2002).

The gas permeability of the snowpack on ski pistes is strongly decreased by the formation of ice layers (Newesely 1997). Due to the respiration of soil microorganisms, the oxygen concentration at the soil surface can be decreased if gas exchange between the snow surface and the snow base is hindered. Hence, oxygen concentrations at the soil surface can be reduced to 5% (Newesely et al. 1994), whilst the carbon dioxide concentration can reach 8% (Cernusca et al. 1990). One of the various effects of oxygen deficiency on plants is that it may cause suitable conditions for fungi and pathogens, e.g. snow mould. Moreover, oxygen deficiency makes plants more sensitive to frost damage (Newesely 1997; Körner 1999). Therefore, ice layers can have negative effects on plants.

The disadvantageous winter snow conditions on the ski pistes results in a delayed development of the vegetation in Russian ski areas (Baiderin 1981), where plant species developing early in the year are suppressed in comparison to species with a late-season development. Similar tendencies were found on Swiss ski slopes (S. Wipf et al., unpubl. data) where the cover and species number of early-flowering species were lower on than beside ski pistes.

The grooming of the snow on ski pistes apparently results in mechanical damage to the vegetation (e.g. Mosimann 1985; Wardle & Fahey 1999). Especially under a thin snow layer, it seems plausible that plants are damaged by the heavy machines and the sharp edges of skis. On Swiss ski pistes, woody plants are in particular reduced on ski pistes (S. Wipf et al., unpubl. observ.).

A major disturbance factor on ski pistes is ground levelling. Ground levelling is a measure carried out in summer to eliminate rocks and to smooth pistes allowing an early start of the ski season. It is usually a one-time measure with long-term impacts on the environment. The influence of ski piste levelling on the vegetation has been investigated extensively for decades. The species composition of the vegetation is transformed, the productivity is decreased and the soil is more likely to erode (Leser et al. 1982; Cernusca 1984; Tsuyuzaki 1991, 1993, 1995; Bayfield 1996; Titus 1999). The revegetation of levelled ski pistes appears to be difficult at high elevations. Above the timberline levelled areas remain visible for decades (Bayfield et al. 1984; Urbanska 1990, 1994, 1995; Delarze 1994). At very high altitudes, the levelling of ski pistes can enhance the thawing of permafrost (Haeberli 1982, 1992).

In recent years, the production of artificial snow (also called 'man-made snow' or 'technical snow') has become an increasingly important issue in most ski areas of the world (Mosimann 1998) (Table 1, Fig. 1). Climate scenarios forecast a rise of 300 m in elevation where winter sport is economically viable from 1200 to 1500 m a.s.l. within the next 25–50 years (Bürki 1998). Therefore, ski resorts at elevations lower than 1500 m a.s.l. might not obtain enough snow to maintain a profitable winter sports industry.

Another problem besides changing winter snow conditions arises from the increasing demands of ski tourism. To meet the tourists' expectations, winter sport has to be possible very early in the winter season, as early as November in the northern hemisphere, when the natural snow fall is often sparse. Due to this reason, mountain railway companies invest increasingly in the production of artificial snow. In 2001,

Table 1. Extent and development of artificial snow production in the Alps based on CIPRA (1998) (–, no information). No information is available from Italy and the Scandinavian countries. Therefore, the numbers for Europe are considerably higher than the sums of values from the five countries in Table 1.

	Snowing facilities 1995 (%)[1]	Area with snow production 1995 (ha)	Number of snowing facilities	
			1992 (*1990)	1996 (*1995)
Austria	54.6	3848	175	300
Switzerland	23.7	1000	26*	130*
France	18.2	1560	60	100
Germany	1.9	121	–	10
Slovenia	1.6	109	–	9

[1] Percent of total in the Alps without Italy.

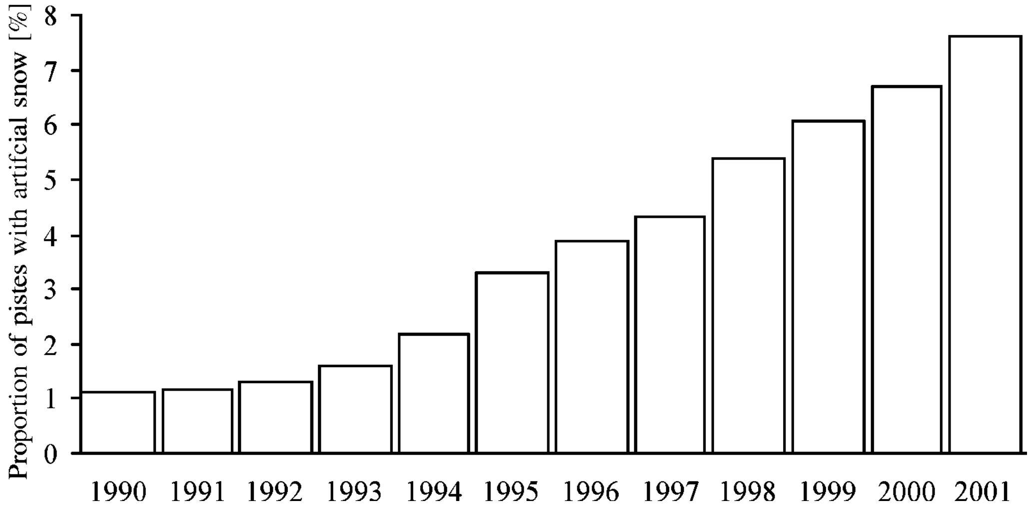

Fig. 1. Increase of artificial snowing in Switzerland (percentage of the total ski piste area covered with artificial snow; data from Seilbahnen Schweiz 2001.

7.6% of the total ski pistes area in Switzerland was covered with artificial snow (Fig. 1), and the snow production continues to increase. In the United States, 59% of all ski resorts already relied on snowmaking in 1984 (Kocak & van Gemert 1988), compared to approximately 90% in 2001.

Another issue in ski areas are snow additives that are increasingly used for snow production. These additives are products with ice nucleation activity (INA) that enhance ice crystal formation. The INA material consists of sterilised phytopathogenic bacteria (Hirano & Upper 2000). Besides the ice nucleation additives, salts (mostly chlorides and nitrates) are used for ski piste preparation after the snow has been distributed on the piste. The purpose of the salts is to harden the snow for ski races by creating an icy surface (Kobayashi et al. 2000).

Artificial snow production and the use of snow additives raise various conflicts with other interests within the alpine environment (Broggi & Willi 1989). Farmers fear that the productivity or fodder quality of pastures or meadows might be affected. Conservationists are concerned about a possible new hazard to sensitive habitats and an endangerment of rare species because of potential inputs of nutrients and snow additives (Bayfield & Barrow 1985; Price 1985; Meisterhans 1988; WWF 1995; Ries 1996). Facilities for snow production affect the landscape aesthetics and, furthermore, snow production consumes energy and water (Baron et al. 2000) and causes considerable noise. On the other hand, it has been argued by snow producers that artificial snow may protect the ski piste vegetation and thus should be considered as an ecological improvement.

In this review, we examine how the addition of artificial snow modifies the general impacts of ski pistes described above, and whether it mitigates the negative effects of ski piste preparation. In particular, we will explain if artificial snow mitigates or enhances soil frost, the development of ice layers, the delay of vegetation development and the mechanical damage to plants. The ecological impacts of these factors will be discussed. Furthermore, we will address the additional environmental impacts of snowing, namely the input of water and ions and the input of snow additives. Despite the fact that artificial snow is extensively and increasingly applied, many aspects have not yet been fully investigated. Thus, we will point out open questions, ongoing research and future challenges throughout the review.

How is artificial snow produced?

Water, air, energy and temperatures below freezing are required to produce artificial snow with most of the common snowing facilities. During the snowmaking process, water is atomised by spraying water into the air with snow machines (Fig. 2). Given sufficiently cold temperatures, the water droplets freeze in the air and fall to the ground as snow.

Usually, temperatures of less than –7 °C are required for the water droplets to freeze on their way to the ground (Fauve et al. 2002). If ice nucleates are added to the water, snow can be produced at temperatures up to –3 °C. The most common ice nucleate is 'Snomax®', a product that contains the sterilised bacteria *Pseudomonas syringae* (see below).

The properties of artificial snow are in many respects different from natural snow. Unlike the common star-shaped natural snow flakes, artificial snow consists of round grains (Fig. 3). The water for snowing is usually taken from water reservoirs, rivers, lakes or springs and thus differs in its chemical composition from precipitation water (for effects on snow density and chemical properties see below).

Does artificial snow mitigate negative environmental impacts of ski pistes?

Subnivean temperatures and soil frost

The snow on snowed pistes is both denser and deeper than the snow on un-snowed pistes (Rixen 2002). Basically, dense snow results in decreased and deep snow in an increased insulation of the soil. The temperature conductivity in compacted artificial snow was found to be about 2.5 times higher than in incompact natural snow, while that of compacted natural snow was only 2 times higher than in incompact natural snow (Geiger 1961; Cernusca et al. 1990). However, temperature measurements at the soil surface showed higher values under the snowed than under the un-snowed pistes (Newesely 1997; Rixen 2002). The temperature regime at the soil surface beneath artificial snow was similar to that under incompact snow with temperatures around the freezing point and soil frosts lasting only for short periods. Thus, the increased snow depth is the more important parameter for the subnivean temperatures than the increased snow density under the given snowing practises.

The decreased temperatures and resulting soil frost under pistes with natural snow have major impacts on the environment. The changed temperature regime, especially induced soil frost, can increase lateral surface runoff (Kokelj & Lewkowicz 1998) and thus increase erosion. It has been hypothesised that the soil cooling could even induce permafrost at high elevations which would obviously have considerable impacts on the environment (Haeberli 1982, 1992). Winter soil temperature regime can directly affect plants. For example, the white clover *Trifolium repens* suffered from frost damage on ski pistes (Newesely 1997). A soil freezing experiment suggested that fine roots were damaged mechanically by soil frost (Tierney et al. 2001). Plants can as well be indirectly affected via soil microbial activity (Williams et al. 1995). Microbes can be active below 0 °C (Brooks et al. 1996) and thus have an impact on the nitrogen cycling in the soil (Brooks & Williams 1999) and the nitrogen availability for plants even during the winter. Hence, preventing frost in soils that are usually not exposed to temperatures much below freezing can be considered as beneficial.

Fig. 2. Production of artificial snow. Water is atomised through nozzles of snow machines into droplets and blown into the air with a built-in fan or with high pressure. The droplets usually require temperatures of below –7 °C in order to be frozen thoroughly when they fall to the ground as snow.

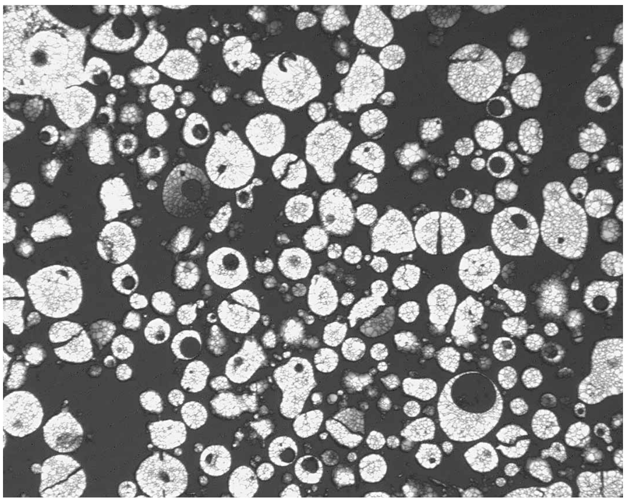

Fig. 3. Artificial snow grains (thin section 0.03 mm, 2 mm × 2 mm); liquid water in some grains. Some grains broken from pressure during freezing process (from Fauve et al. 2002).

Ice layers

Ice layers can develop in the snowpack when the snow is intensively compacted by snow-grooming vehicles. On unsnowed pistes ice is likely to develop earlier in the winter than on pistes with artificial snow, because the soil has less insulation (Newesely 1997). On the other hand, the ice layers in artificial snow remain until late winter. Furthermore, if artificial snow is not completely frozen due to high temperatures and groomed to early, additional ice layers can be the consequence (Fauve et al. 2002). Thus, adding artificial snow does not necessarily mitigate the formation of ice layers in the snowpack.

The ice layers strongly affect the gas permeability of the snow cover (Newesely 1997). When the gas exchange between the snow surface and the snow base is hindered, the active microorganisms in the soil use up the oxygen and produce carbon dioxide.

Delayed plant development

The additional mass of artificial snow on snowed pistes takes longer to melt, which leads to prolonged snow cover in the spring (Fig. 4; Aarrestad 1993; Stoeckli & Rixen 2000; Rixen et al. 2001). Snowmelt can be postponed by up to four weeks compared to pistes with natural snow (on average 17 days; Rixen 2002). Consequently, the phenology of plants is delayed by several weeks. Even a minor experimental delay in snowmelt of two days at the end of April resulted in a delay of flowering in *Taraxacum officinale* agg. in mid June (Rixen et al. 2001). On ski slopes in Savognin, Switzerland, Kammer & Hegg (1990) determined that the time span between the snowmelt of artificial snow and the first cut of hay meadows was too short to ensure the seed set of all meadow species. Hence, the artificial snow does not mitigate the delayed development on the ski pistes. Rather, it delays

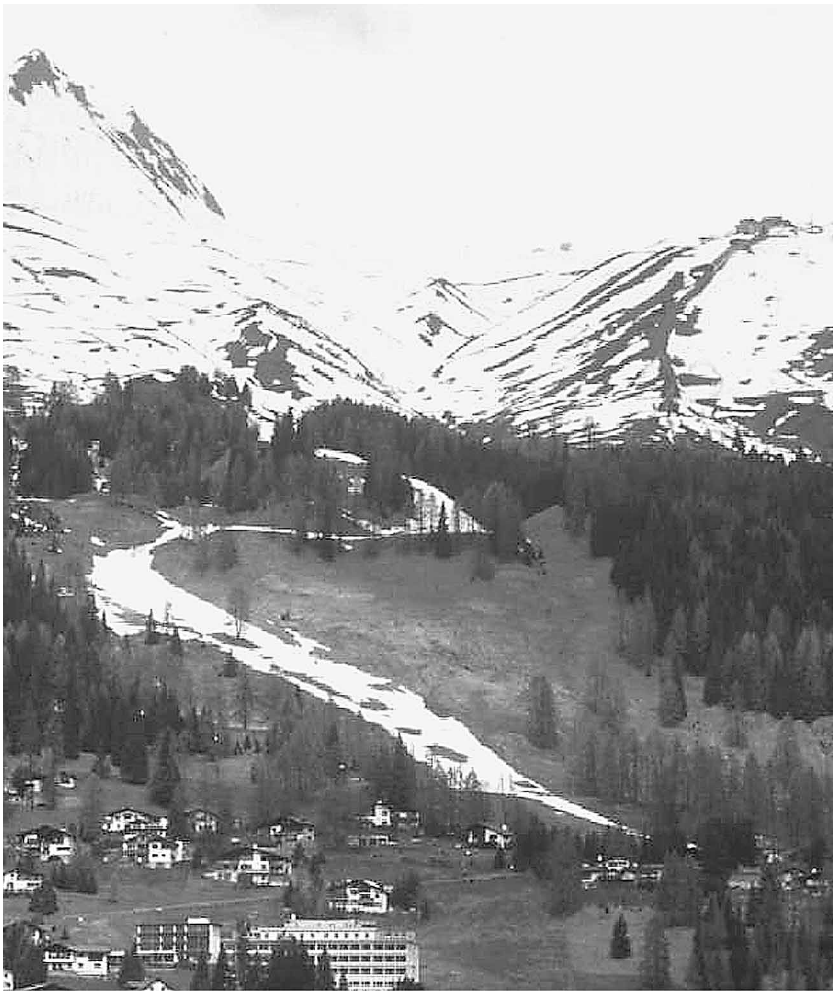

Fig. 4. Delayed snowmelt on ski piste with artificial snow in Davos, Switzerland. Where artificial snow is applied, snowmelt may be four weeks later than at sites with natural snow.

the plant development even more because of the late snowmelt.

Reactions of the vegetation composition to a delayed development have been reported in several studies. Knight et al. (1979) analysed how the plant species composition and the growth of subalpine dry and mesic meadows responded to the addition of snow during five years. Plant growth was delayed by about 7–9 days when snow was added. Plant species from high elevation habitats, such as *Sibbaldia procumbens*, increased in biomass during the five year experimental period. On the Swiss ski slopes different ecological groups of species were favoured on the snowed and un-snowed pistes types (Wipf et al. 2002). On pistes with natural snow, plant species were favoured that usually inhabit so-called wind edges. Wind edges are characterised by a thin snow cover and extremely low winter temperatures (Körner 1999), like those on ski pistes with natural snow. On pistes with artificial snow, so-called snowbed species were enhanced. Snowbeds are characterised by a long-lasting snow cover and short vegetation period (Körner 1999), like on pistes with artificial snow.

The influence of the snowpack on the productivity of the vegetation depends on the climate. Snow augmentation decreases the productivity of mesic vegetation und humid climatic conditions (Weaver & Collins 1977; Stoeckli & Rixen 2000). However, in an arid climate like for example in eastern parts of the Rocky Mountains, plant growth is less limited by the length of the vegetation period than by the availability of water. Therefore, productivity is often increased by a deeper snow cover (Knight et al. 1979; Price & Waser 2000).

Mechanical damage

The snow depth is increased by artificial snowing due to the additional amount of snow cast on the pistes (e.g. Newesely 1997; Rixen 2002). This is an advantage for plants as they are better protected against mechanical damage. Woody plants that have sensitive tissues above the ground in winter (see Fig. 5) were an example for protective properties of artificial snow (S. Wipf et al., unpubl. observ.). They were decreased in abundance on ski pistes in general compared to control plots beside pistes, but they were more abundant on pistes with artificial snow than on pistes with natural snow. This suggests that they benefit most from increased snow depth. Therefore, woody plants indicate that artificial snow mitigates the mechanical disturbance to the vegetation through snow-grooming vehicles and skiers.

Input of water and ions

The production of artificial snow results in an extra input of water to the ski pistes. According to Mosimann (1998), the water input from artificial snow usually reaches 0.7 to 2 times, sometimes up to 5 times that

Fig. 5. Dwarf shrub (*Rhododendron ferrugineum*) on ski piste with natural snow. Woody plants suffer less mechanical damage when protected by an artificial snow cover.

from natural snow. Usual amounts of water applied as artificial snow are 100–600 mm (Mosimann 1998). These values were confirmed by a Swiss study, where the average water input from the melting snowpack was almost double the natural level (approx. 750 mm vs. 400 mm, Stoeckli & Rixen 2000). This may change the local hydrology and increase the erosion intensity. As the water used for snowmaking is usually pumped from rivers, lakes or ground water sources, it is enriched in minerals from the catchments, including ions that are essential for plant growth, such as Ca^{2+}, Mg^{2+}, Na^+, K^+, Cl^-, SO_4^{2-}, NH_4^+ or NO_3^- (Table 2).

The vegetation composition changes in response to inputs of water and ions. A study near Savognin, Switzerland, showed that the artificial snow led to changes in mesotrophic habitats, like grasslands with little fertilisation (Mesobrometum-Trisetetum vegetation; Kammer & Hegg 1990). Plants tolerant of dry, low-nutrient conditions (e.g. *Koeleria pyramidata, Silene nutans, Thymus pulegioides*) were replaced by more common mesic and nutrient-demanding species (e.g. *Chaerophyllum hirsutum, Myosotis silvatica, Pimpinella major*). Changes were less pronounced on fertilised meadows. In soils down to a depth of 15 cm, Kammer & Hegg (1990) recorded significantly higher pH-values on snowed piste compared to control plots. They attributed them to the high pH of the river water that was used for snow production. In 13 ski resorts in Switzerland similar changes were suggested by differences in the ecological indicator values (Landolt 1977): Moisture and nitrogen values were higher on snowed pistes than at control plots besides pistes (S. Wipf et al., unpubl. data). A Canadian study analysed the effects of watering with melt water from natural or artificial snow on the germination success of birch and spruce trees but failed to show any significant differences (Devarennes 1994).

Table 2. Chemical composition (electrical conductivity and ionic contents) of melt water from artificial and from natural snow (mean from 10 ski resorts in Switzerland ± SD). Artificial snow was sampled on ski pistes and actually represents a mixture of layers of artificial and natural snow. Natural snow was sampled beside the ski pistes. Statistically significant differences were tested with LSD tests based on t-tests (ns, $P \geq 0.05$; *, $P < 0.05$; **, $P < 0.01$).

	Artificial snow	Natural snow	P
Electrical conductivity (µS)	61 ± 30	15 ± 7	**
Ca^{2-} (mg l^{-1})	5.34 ± 3.12	0.71 ± 0.51	**
K^- (mg l^{-1})	0.75 ± 0.43	0.75 ± 0.28	ns
Mg^{2-} (mg l^{-1})	1.28 ± 1.32	0.09 ± 0.06	*
Na^- (mg l^{-1})	2.18 ± 2.23	1.03 ± 0.46	ns
Cl^- (mg l^{-1})	3.12 ± 4.31	1.18 ± 0.69	ns
SO_4^{2-} (mg l^{-1})	6.38 ± 5.84	0.47 ± 0.20	*
NO_3^- (mg l^{-1})	0.64 ± 0.26	0.53 ± 0.21	ns
NH_4^+ (mg l^{-1})	0.01 ± 0.06	0.14 ± 0.06	*

It is not clear, what fraction of the ionic input can be taken up by plants and how much percolates through the soil. However, it has been shown that alpine plants can take up considerable amounts of nitrogen during early spring snowmelt (Mullen et al. 1998; Bilbrough et al. 2000). This ability might be especially important as ions are not washed out of a snowpack evenly but in sequential ionic pulses (Abrahams et al. 1989). Hence, plants are probably able to take up additional ions and nutrients from the melt water that derives from the artificial snow even if the vegetation period has not yet started.

The water that is used for artificial snow is taken from a water source like rivers, lakes or springs. As the water table of rivers is low in the winter anyway, removing water enhances the drying of streams even more (WWF 1995). If water is taken from springs or if water reservoirs are built, the hydrology of alpine ecosystems, especially fens, is negatively affected. However, this has not been investigated yet.

Input of snow additives

Adding ice nucleation active (INA) bacteria to water enables snow production at temperatures of approximately −3 °C, whereas without snow additives temperatures lower than −7 °C are needed (Maki et al. 1974; Gurian-Sherman & Lindow 1993). It has long been known that various nuclei can stimulate the formation of ice (Mason & Hallett 1957). Especially effective nuclei were found on decomposed leaves in 1972 (Schnell & Vali 1972, 1973). In 1974, cultures of *Pseudomonas syringae* (31 A) isolated from North American alder leaves (*Alnus tenuifolia*; see Hirano & Upper 2000) showed ice nucleating properties, causing water to freeze at the relatively warm temperatures of −1.8 to −3.8 °C (Maki et al. 1974). The bacteria contain proteins that resemble the structure of ice crystals and thus enhance the formation of ice (Wolber & Warren 1989; Pattnaik et al. 1997). The product 'Snomax' (Kocak & van Gemert 1988) contains sterilised *P. syringae*. Related species used in other INA products are *Erwinia herbicola* and *Xanthomonas campestris*.

According to Brown (1997), INA products are used in about half of North American ski resorts. During the 1994 Olympic games in Lillehammer all of the artificial snow was produced with Snomax. In the Alps the use of Snomax depends on the legislation of the different countries and regions. While in Germany and Italy the use of snow additives is forbidden no regulations exist in France. Within Switzerland and Austria the handling of this issue differs from region to region (Bonjour & Carle 1997). The input of INA substances can influence the ecosystem in different ways. The most important concerns about using bacterial products in the alpine environment are potential pathogenic effects on plants either from surviving bacteria or from toxins in dead bacteria and an increased ice nucleation activity on plant tissue.

Salts are used for ski piste preparation, especially on race pistes, to improve the snow quality for skiing purposes, for example, if snow is too cold, too sticky or hard ice (USSA 1996; Raguso 2000). Comparable to salts used on roads, the chemicals used on ski pistes melt the uppermost layer of the snowpack and thus change the snow quality (Kobayashi et al. 2000).

Different salts are used depending on weather and snow conditions because the different salts vary in their snow melting properties. Among the most common salts are ammonium nitrate (PTX™), ammonium chloride, ammonium sulphate, potassium chloride, sodium chloride and phosphates (Raguso 2000).

Salts are more likely to be used on ski pistes with artificial snow because, given the economical importance of ski races, ski resort managers will normally not rely on natural snow only. Artificial snow, however, is of course not necessarily required for ski races. The salts can be used occasionally when weather conditions require it for races, or on a regular basis to enable summer skiing on snow fields (Sno-Engineering 1996).

Pathogenic properties

Phytopathogenic effects of INA products on plants may occur if the product still contains live bacteria after sterilisation, or if toxins from dead bacteria are still effective. Phytopathogenic effects of live *P. syringae* (31A) on 53 non-alpine plant species were tested in Switzerland (see Bonjour & Carle 1997), and 3 of the 53 species showed chloroses. However, as alpine species were not tested, effects of *P. syringae* on alpine vegetation remain unclear. Even effects on vertebrates cannot be excluded as rats reacted with enlarged lymph nodes to the inhalation of aerosols containing nucleation-active *P. syringae* (Goodnow et al. 1990).

Ice nucleation activity (INA)

The presence of *P. syringae* on the surface of leaves can cause damage to plant cells by increasing the threshold temperature for the freezing of water. Enhanced plant tissue damage has been observed in buds of pears (Panagopoulos & Crosse 1964) and peaches (Wisniewski et al. 1997) infected with *P. syringae*. Lindow et al. (1978) found *P. syringae* on the surface of 74 out of 95 analysed species sampled from several locations (mostly not alpine) in North America. Bacteria numbers were potentially sufficient to cause freezing injury in plants. Only conifers showed infrequent colonisation by INA bacteria. Freezing experiments in growth chambers with *Thymus serpyllum* and *Trifolium repens* showed no differences in the extent of frost damage between leaves with Snomax solution on the surface and those with control water (Rixen 2002). These results, however, do not prove that there are no possible effects of INA material, and it remains unclear to what extent alpine plants could be affected by substances with INA. It can be hypothesised that the plants' sensitivity depends on the respective physiological processes for dealing with extreme cold. Plant tissues can either avoid freezing by using 'anti-freeze'-based supercooling or can tolerate freezing (Körner 1999). Plant organes that can tolerate freezing are unlikely to be affected by INA bacteria, whereas plants with a supercooling strategy could be seriously harmed by substances enhancing the formation of ice crystals. This hypothesis, however, has yet to be proved. Supercooling is frequent in small cells, such as in buds or seeds, that only need to cope with relatively short periods of extreme cold. Freezing tolerance is more likely to occur in plants or tissues adapted to long-term low temperature extremes (Körner 1999). In terms of the growth forms of alpine species, supercooling is more common in relatively tall shrubs and freezing tolerance more common in low-stature plants.

INA tests of snow, plant and soil samples from different ski pistes where snow was produced with and without Snomax were carried out by Wallis et al. (1988, 1989) but left uncertainties. INA tests on plants and in snow yielded ambiguous results but soils showed a higher ice nucleation activity on the ski piste with Snomax. However, the authors of the INA study could not conclude whether or not INA substances percolate into the soil whilst retaining their activity. Furthermore, ice nucleation activity is not necessarily only caused by *P. syringae*. Other natural sources could have been the reason for the increased INA found in the soils investigated by Wallis et al. (1988, 1989). The remaining open questions have not been addressed since this study.

Survival of *Pseudomonas syringae* in the alpine environment

In a series of laboratory experiments, Goodnow et al. (1990) tested the survival rate and the INA of *P. syringae* in snow, soil and water. The snow was produced with a *P. syringae* content of 0.08 mg l^{-1}. It was kept in the dark for 21 days during which it was defrosted and refrozen 20 times. After this treatment, less than 3% of the bacteria survived, but the INA was still at 91% of the initial value. In another experiment where the snow was kept in daylight for 7 days, and was also defrosted and refrozen 20 times, no live *P. syringae* bacteria remained, but the INA was still 68% of the initial value. No live bacteria survived in a soil sample kept at 0 °C for 15 days and at 15 °C for 20 days, but 50% survived in a soil at 7.5 °C. In river water stored at 0 °C and 7.5 °C for 25 days, 2% of the bacteria survived, but none survived in water stored at 15 °C. Harrison (1988), who searched for surviving *P. syringae* in alpine waters and soils, came to the conclusion that bacteria survive badly in alpine environment. However, the survival of *P. syringae* in the alpine environment cannot be dismissed. More research is needed, but no further investigations have been carried out since 1990.

Impact of INA products on plant productivity

Irrigation experiments in the greenhouse with three alpine–subalpine plant species demonstrated that plant growth responds to Snomax solutions but the effects were inconsistent (Rixen 2002): *Trisetum flavescens* showed increased biomass production when irrigated with Snomax solution, probably due to the input of organic nitrogen, whereas the biomass production of *Trifolium repens* and *Thymus serpyllum* was decreased. While it is possible that the symbiosis of *T. repens* with its N-fixing bacteria was affected by the N input, reasons for the reduced growth of *T. serpyllum* must be found elsewhere. It is unlikely to be due to nitrogen levels in the experiment which were not at toxic levels.

Input of salts

The ecological effects of salts on ski pistes have been addressed in only few studies (Sno-Engineering 1996; Rixen 2002), unlike the effects of de-icing salts on road verges (e.g. Richburg et al. 2001; Bryson & Barker 2002). Near a snowfield in Oregon with summer skiing where up to 500,000 kg of salts were used from May to September, chloride concentrations of streams within the drainage of the snowfield were around 30 mg l^{-1} compared to 1–6 mg l^{-1} outside the drainage (Sno-Engineering 1996). In an experiment on plant growth, the amount of a single application of PTX (50 g PTX m^{-2}, equivalent to 17 g N m^{-2}) significantly increased the biomass production of alpine meadows (608 g m^{-2} vs. 439 g m^{-2}; Rixen 2002). Salt toxicity to plants on ski pistes as observed at road verges (Bryson & Barker 2002) has not yet been investigated.

Any other indications for impacts of salts on alpine vegetation have to be extrapolated from experiments with mineral fertiliser in alpine regions that can only briefly be described here. Such studies have shown that even at high altitudes plant growth reacts strongly to NPK fertilisation (Heer & Körner 2002), and that long-term effects of N, P, K and Ca fertilisation on plant species composition can still be detectable 50 years after the last application (Hegg 1984). However, the reactions of plants to mineral fertiliser may be more complex than just increased growth (Körner 1984): After fertilisation, the shrub species *Vaccinium uliginosum*, *Loiseleuria procumbens* and *Rhododendron ferrugineum* showed an increase in shoot length, ramification and leaf size but not in radial growth of the stems. This might make the shrubs more sensitive to mechanical stress due to a taller stature (Körner 1980). Furthermore, the fertilised *Loiseleuria* suffered from snow mould infestation, and *Vaccinium* displayed an earlier bud break in spring, making the plant more vulnerable to late frosts. These results show that fertilising salts can increase the sensitivity of dwarf shrubs to the harsh alpine environment. The impacts of fertiliser inputs can, furthermore, depend on the kind of fertiliser used (Seastedt & Vaccaro 2001). The addition of nitrogen reduced the species richness of alpine vegetation in Colorado whereas the addition of phosphorous did not. These results can only partly be transferred to ski pistes, however, they may indicate that salts and fertilisers have negative impacts on the ski piste vegetation by decreasing its species diversity.

Conclusions

Several studies have shown that the production of artificial snow and the preparation of ski pistes in general influence various aspects of the alpine environment. Changes due to snow treatment are related to changes in snow depth and density, insulation properties, gas permeability and duration of the snow cover. Soil properties and plant species composition are changed as a result of these changed environmental conditions.

The environmental impacts caused by ski pistes in general are modified by artificial snowing. The severe soil frosts that are caused by decreased insulation of the snow on ski pistes are mitigated by the addition of artificial snow. Increasing the snow depth with artificial snow increases the insulation properties of the snowpack. Ice layers that develop in the snowpack due to compaction with heavy machinery and decrease in gas permeability are not lessened by snowing. Neither does artificial snowing mitigate a delayed vegetation development on ski pistes, it rather enhances the late development due to a strongly delayed snowmelt. However, the artificial snow increases the mechanical protection of the plants under the snow and thus mitigates mechanical impacts of snow-grooming vehicles on ski pistes. Overall, the mitigating properties of snowing are not unambiguous enough to be clearly beneficial.

Artificial snow induces new impacts to the environment beyond modifying the impacts of ski pistes in general. The plant species composition is changed by the input of water and ions. Since the responses of the vegetation are increasingly pronounced the longer artificial snow has been applied, we can expect further changes as the production of artificial snow continues. The impacts of the snow additives on the environment have not yet been clearly established. While some studies found no effects of snow additives, others showed impacts on, for example, plant growth, but plants reacted inconsistently. Hence, further investigations into the ecological consequences of using snow additives, especially long-term studies, are needed to improve these preliminary conclusions.

Environmental impacts of skiing and ski piste preparation are not only important environmental issues in terms of nature conservation, erosion and the utilisation of energy and resources in alpine regions. The findings from studies of an artificially changed snow cover can be applied to the issue of climate change, as changes in snow cover distribution are expected to be one consequence of climate changes. Predictions from climate models for snow distribution vary regionally, from decreases in snow depth due to higher temperatures and/or lower precipitation, to increases in snow depth due to higher precipitation. Hence, the examination of ecological changes induced by artificial snowing can, to a certain degree, help when estimating the consequences of climatic changes.

Ecological characteristics and conservation value of a particular area are important to evaluate environmental impacts of ski piste preparation and snow production. Although snowing mitigates some negative impacts of ski piste preparation, it induces some new problems. For instance, in nutrient-poor fens, where for nature conservation reasons any input of nutrients should be avoided, using artificial snow is likely to pose a threat to endangered species. On the other hand, on cultivated land that has been fertilised, a nutrient input would have negligible consequences. In sensitive areas, for example those with rare species, geomorphological peculiarities or a high erosion risk, any ski piste with or without artificial snow can be considered negative, and complete abstinence from ski piste creation should be considered. With respect to snow additives, the snow hardener ammonium nitrate should only be used very restrictively, if at all, and the impacts of other salts and of ice nucleation active substances must be studied more thoroughly. Finally, it must be emphasised that the findings reviewed in this contribution about the impacts of snow production and snow additives probably only represent the beginning of ongoing and increasing future changes. Therefore, new research initiatives should address the remaining open questions, for example, on changed hydrology but also on long-term impacts of snowing and snow additives including salts on the vegetation.

Acknowledgments. We thank Bernhard Schmid, Peter Bebi, Sonja Wipf and Johannes Kollmann for critical reading, and Sabine Güsewell and one anonymous reviewer for constructive and useful comments on the manuscript. This study was supported by the Federal Office for Environment, Forest and Landscape (BUWAL, Switzerland) and the cantons of Grisons and Valais.

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